Motivating a Fusion Power Plant Conceptual Cost Study

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What, why, and how?

What – a cost study for a power plant built around four reactor concepts in the ALPHA program

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Why – estimate capital costs, assess sensitivities, influence follow-on activities

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What – a cost study for a power plant built around four reactor concepts in the ALPHA program

Why – estimate capital costs, assess sensitivities, influence follow-on activities

How – work with a power plant engineering and design firm, augmented by consultants with fusion expertise

What do we mean when I say cost study?

~~**Levelized Cost of Electricity**~~

What we are doing

What do we mean when I say cost study?

- Direct Capital Costs
  - Fusion Power Cores
  - Balance of Plant
  - Tritium Extraction Plant

What we are doing

What do we mean when I say cost study?

- Direct Capital Costs
- Non-Capital Costs (limited)
  - Operations and maintenance
  - Tritium handling and recycling
  - Waste disposal
  - Decommissioning

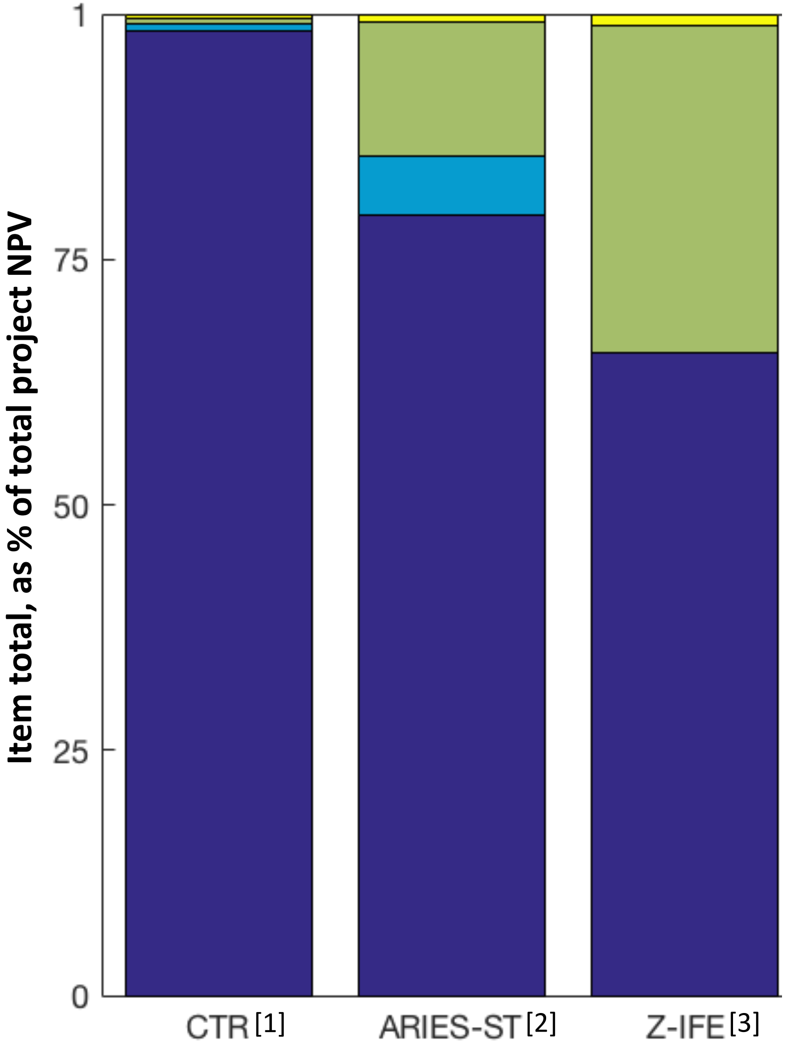
What do we mean when I say cost study?

- Direct Capital Costs
- Non-Capital Costs (limited)

- Excluding
  - Cost of capital / financing costs
  - Cost of start-up tritium inventory
  - Thermal-to-electric efficiency
  - Regulatory costs
  - Research and development costs

What we are doing

Across various fusion power plant designs studies, capital cost is the largest contributor to total net present value



1 – Woodruff, S., Miller, R. “Cost Sensitivity Analysis for a 100 MWe modular power plant and fusion neutron source.” *Fusion Design and Engineering*(2015).
2 – Miller, R. “ARIES-ST design point selection.” *Fusion Design and Engineering*(2015).
3 – Meier, W., Moir, R. “Analyses in Support of Z-Pinch IFE and Actinide Transmutation - LLNL Progress Report for FY-06.” LANL (2006).

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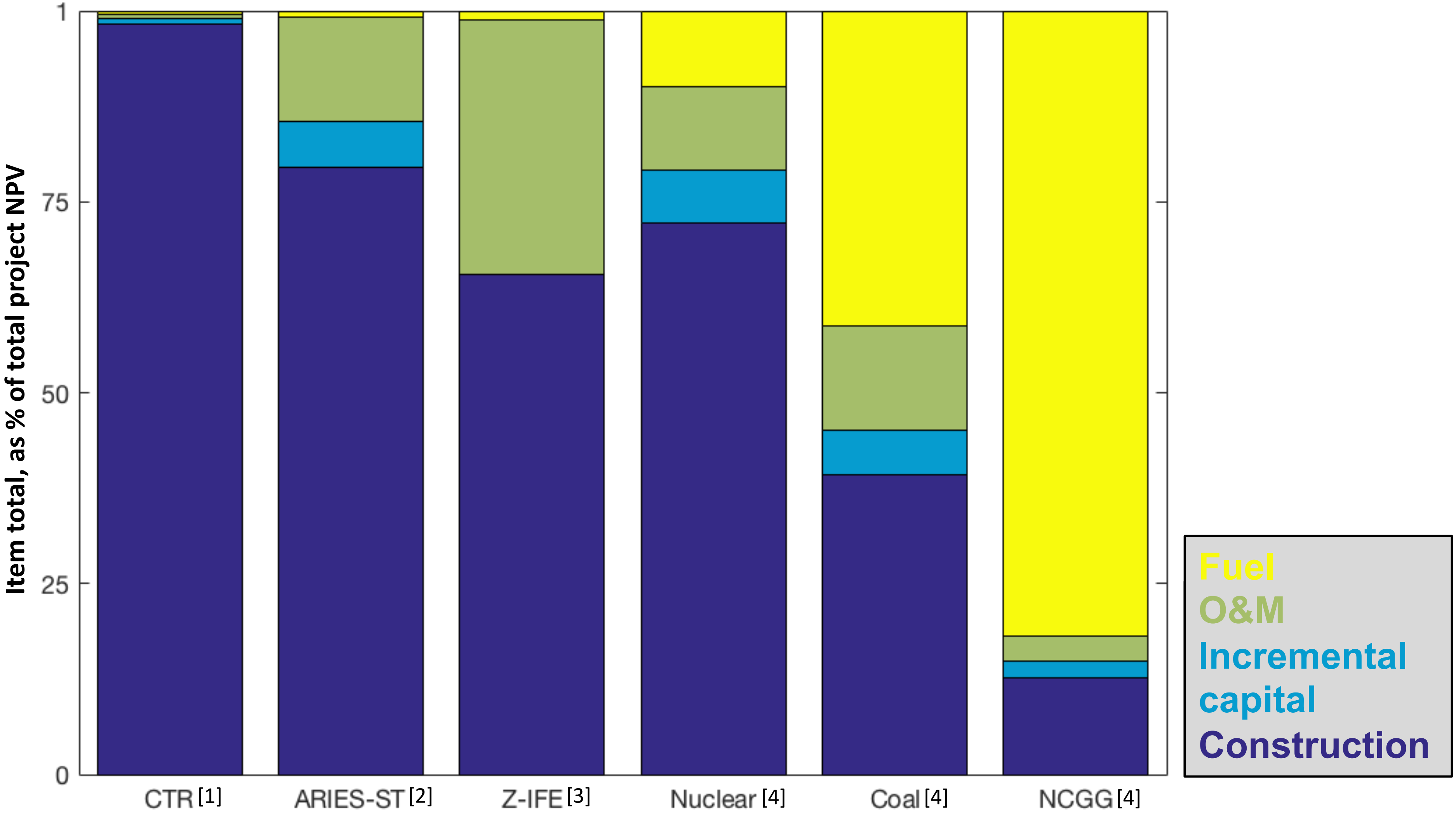

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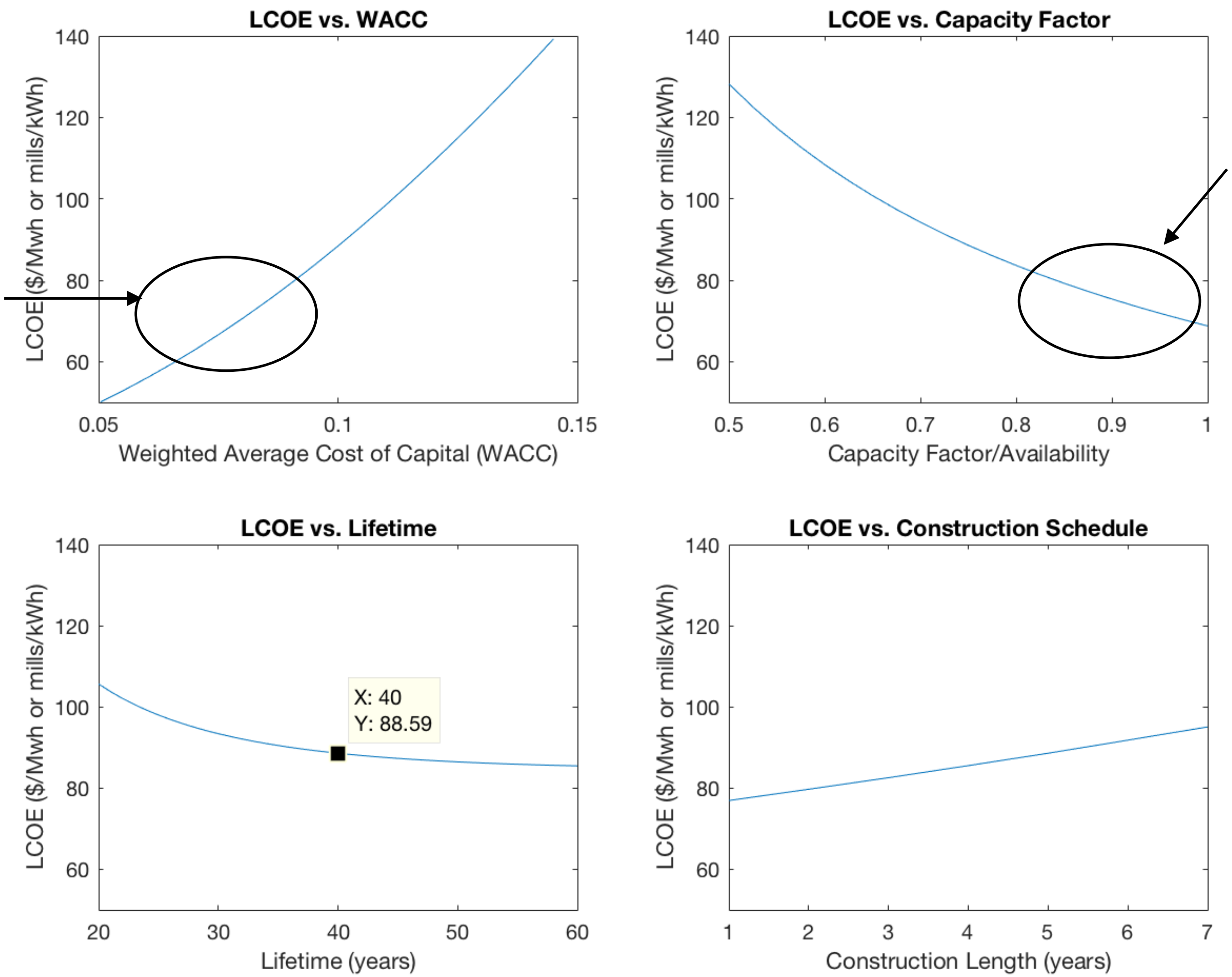
3 – Meier, W., Moir, R. “Analyses in Support of Z-Pinch IFE and Actinide Transmutation - LLNL Progress Report for FY-06.” LANL (2006).
4 – Deutch, J., et al. “Update on the MIT 2003 Future of Nuclear Power.” Massachusetts Institute of Technology (2009).

CHANGING WHAT'S POSSIBLE

Calculating LCOE can be useful but is sensitive to parameters that are unknown for fusion power plants

Low-risk regime

Make them last at least 30 years



High Operational Availability
Low marginal cost

Delays lead to cost increases (even if direct capital remains flat)

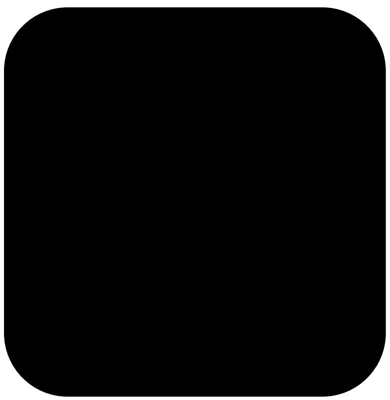
LCOE projections for PPCS-A design (Maisonnier, 2005) using costing information from Han, 2013. LCOE model adapted from MIT spreadsheet model (2009).

Capacity = 1.55 GW, **Specific Capital** = $3,940 $/kW, **Fixed O&M**[1] = $65.8/kW/year, **Var O&M**[2] = 7.78 mills/kWh

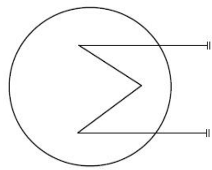
1 - (includes DD costs); 2 - (includes waste disposal)

Driving for a common methodology, approach, and balance of plant to have roughly comparable results

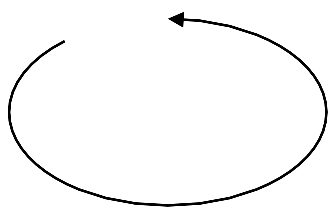
4 x fusion reactors



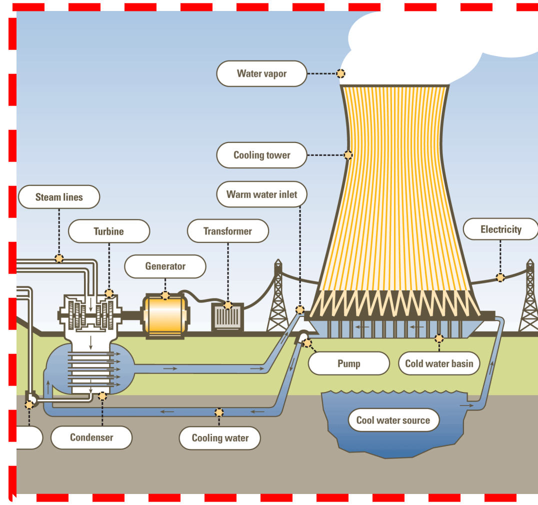
Heat exchange



Tritium extraction and recycling

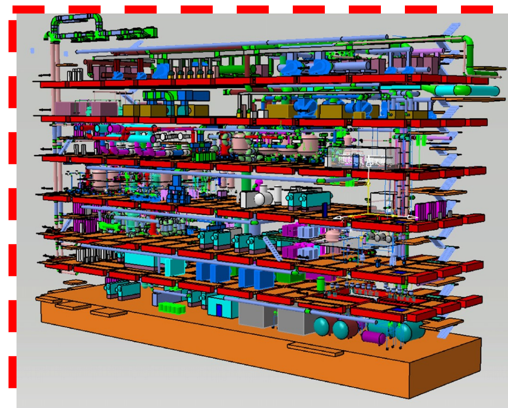


A common balance of plant



Source: www.nerdtrek.com

A common tritium plant



Driving for a common methodology, approach, and balance of plant to have roughly comparable results

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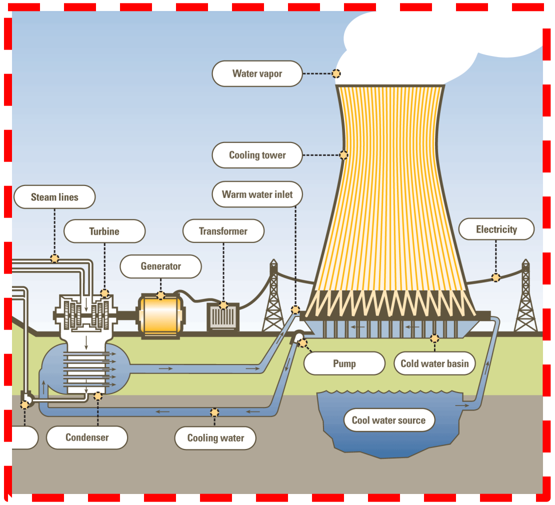

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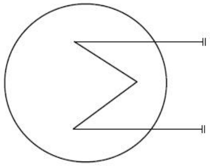
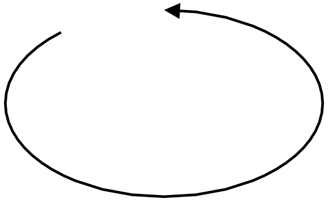
Heat exchange



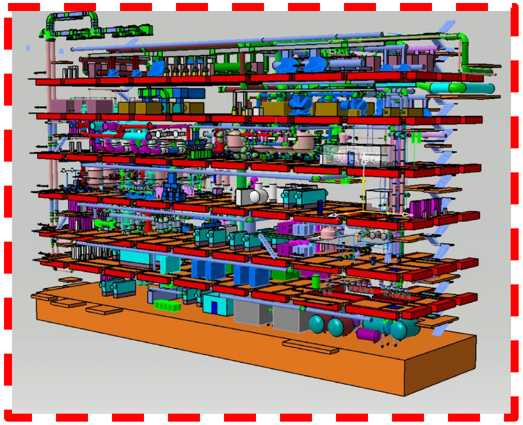
4 x fusion reactors

[redacted]

Tritium extraction and recycling

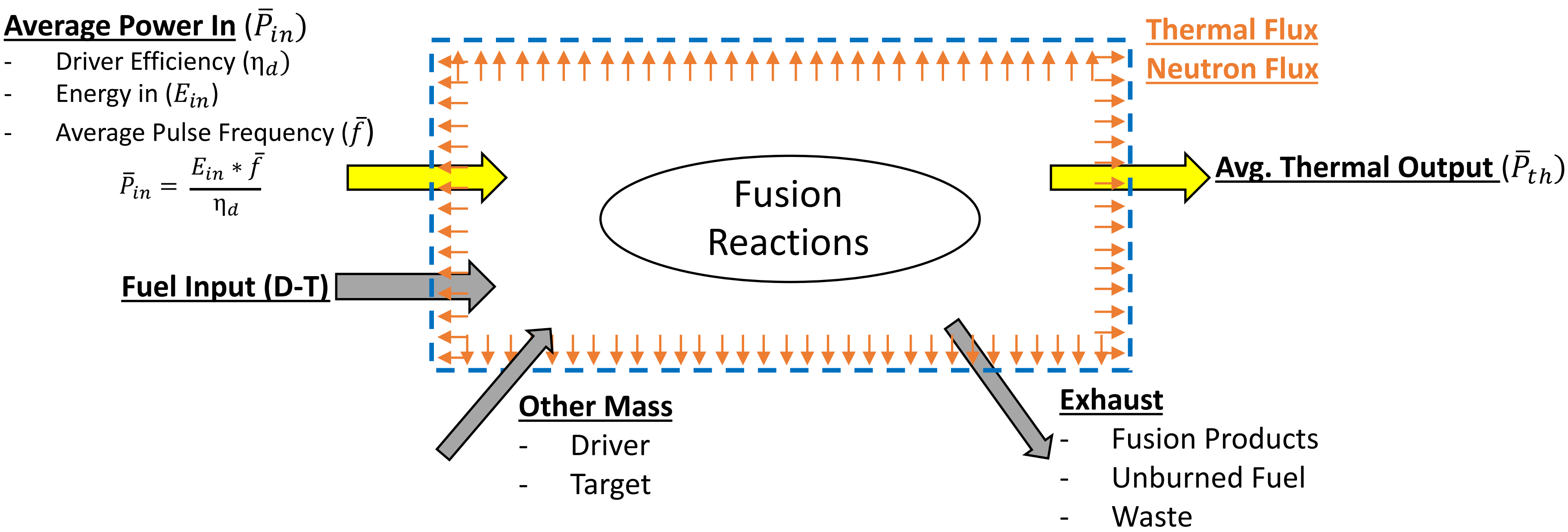


A common tritium plant

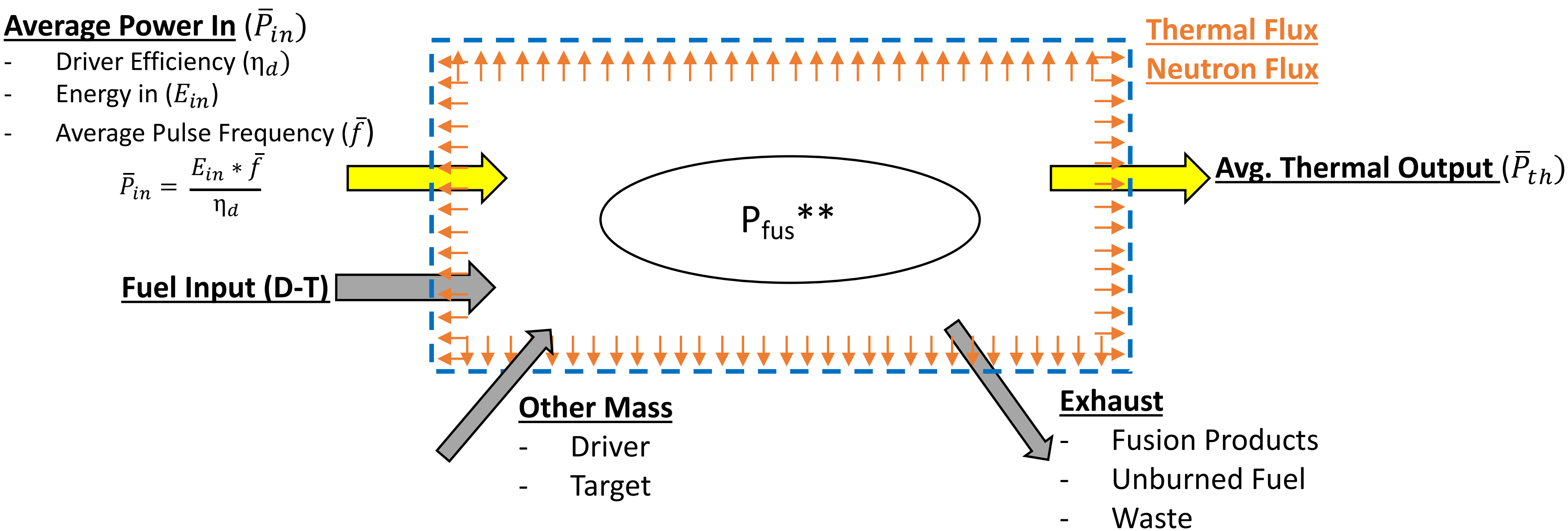


How to find a common set of inputs, boundary conditions, and constraints?

What does a control volume look like for a generic fusion reactor?



What are the parameters and metrics that can link four distinct fusion power cores to a common balance of plant?



Key Parameters

Temperature (T)

Ion Density (n_i)

Confinement Time (τ)

Tritium Fraction (TF)

Burnup Fraction (BF)

Mass Fuel (m_f)

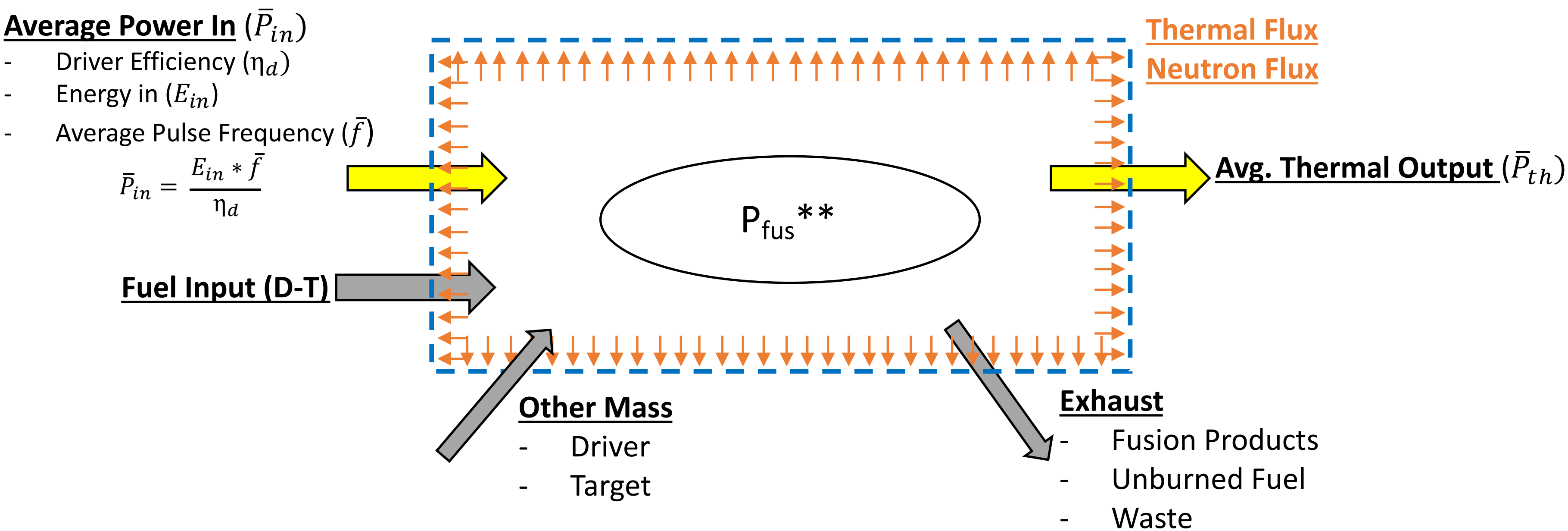
Key Metrics

Thermal Output

Recirculating Power

****Note:** $\bar{P}_{fus}$ does not equal $\bar{P}_{th}$ because of exothermic reactions that may occur in the blanket

What are the dependent variables, boundary conditions, and constraints at play?



Dependant Variable

Capital Cost

Boundary Conditions

P_{th} = 500 MW

Constraints

Recirculating power

Thermal first wall loading

Neutron loading

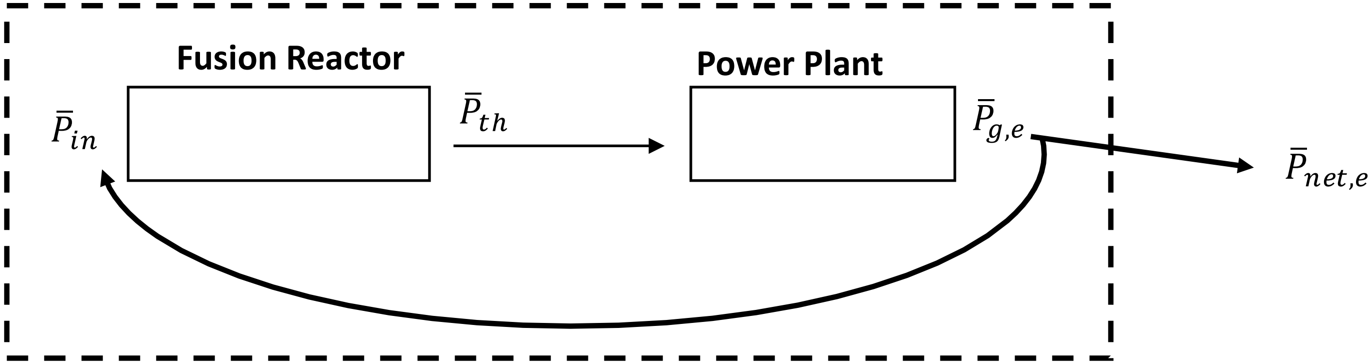
Exhaust handling

Why P_{th} = 500 MW?

- Compatible across concepts for fusion power core
- Smaller size has favorable characteristics
  - Lower-risk profile for investors
  - Relevant and attractive to utilities
  - Manufacturing/repetition rate

Thermal output vs. recirculating power?

- Limit parasitic loads, achieve sufficient net electrical capacity with limited footprint



Constraint: First Wall Thermal Loading

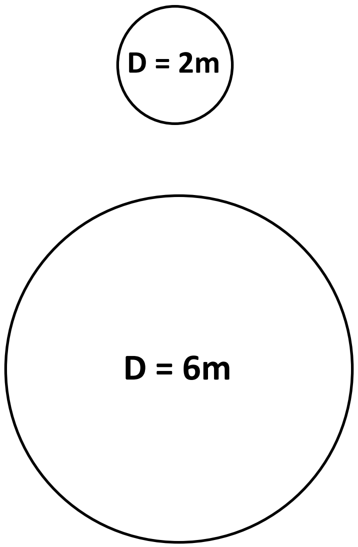
- Challenge: Reactor should not exceed thermal loading envisioned first wall material and design
  - ITER – Enhanced Heat Flux Panels designed for 4.7 MW/m^2 [1]
    - Armor – Beryllium
    - Heat Sink – CuCrZr
    - Structure – Austenitic Steel
  - ITER – Diverter Surface designed for time-averaged 10 MW/m^2, short durations up to 20 MW/m^2[2]
    - Armor - Tungsten

For the Cost Study:

- Geometry / size of reactor vessel should reflect wall loading constraints.

- Dependency between material – thermal constraint – geometry – cost

- Liquid first walls can relax thermal loading constraint



P_{fus} = 500 MW
FW Loading = 39.8 MW/m^2

P_{fus} = 500 MW
FW Loading = 4.4 MW/m^2

[1] – Mazul et. al, "Russian development of enhanced heat flux technologies for ITER first wall." *Fusion Engineering and Design* (2012).
[2] – Merola et. al, "Engineering challenges and development of the ITER Blanket Systemand Divertor." *Fusion Engineering and Design* (2015).

Constraint: Neutronics / Neutron Shielding

- Duel objectives:
  - Moderate fast (14.1 MeV) neutrons to thermal neutrons
  - Protect structure, magnets, and pulsed power systems from neutron damage
- Challenge: The “right way” to scatter and moderate 14.1 MeV neutrons isn’t clear.
- Challenge: Neutron damage will require replacement of components, magnets, and/or pulsed power system

ITER Shield Block [1]

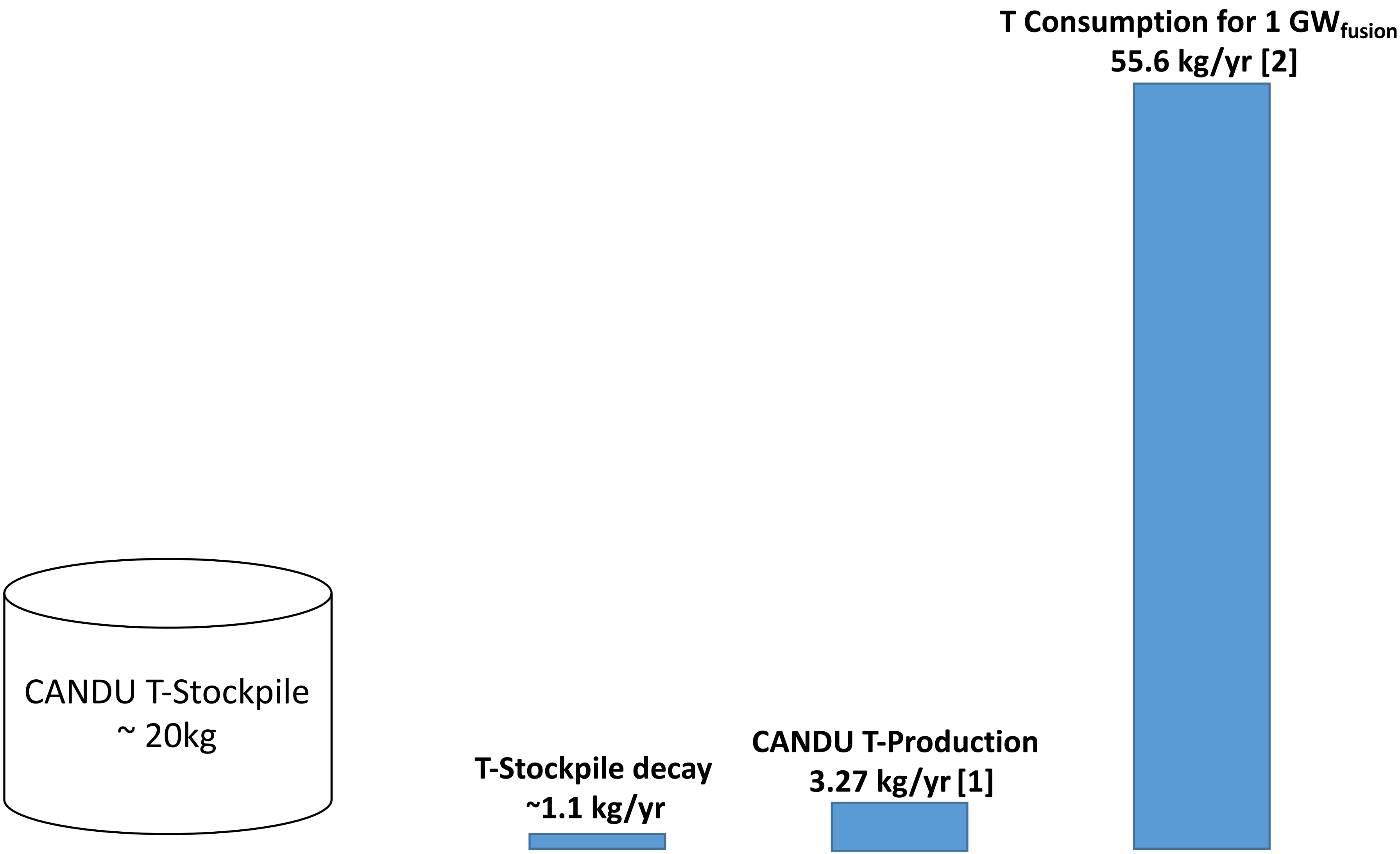
For the Cost Study:

- Recognize and quantify the impact that uncertain neutronic behavior might have on cost

- Dependency between shielding technology – cost – neutron damage – component replacement costs

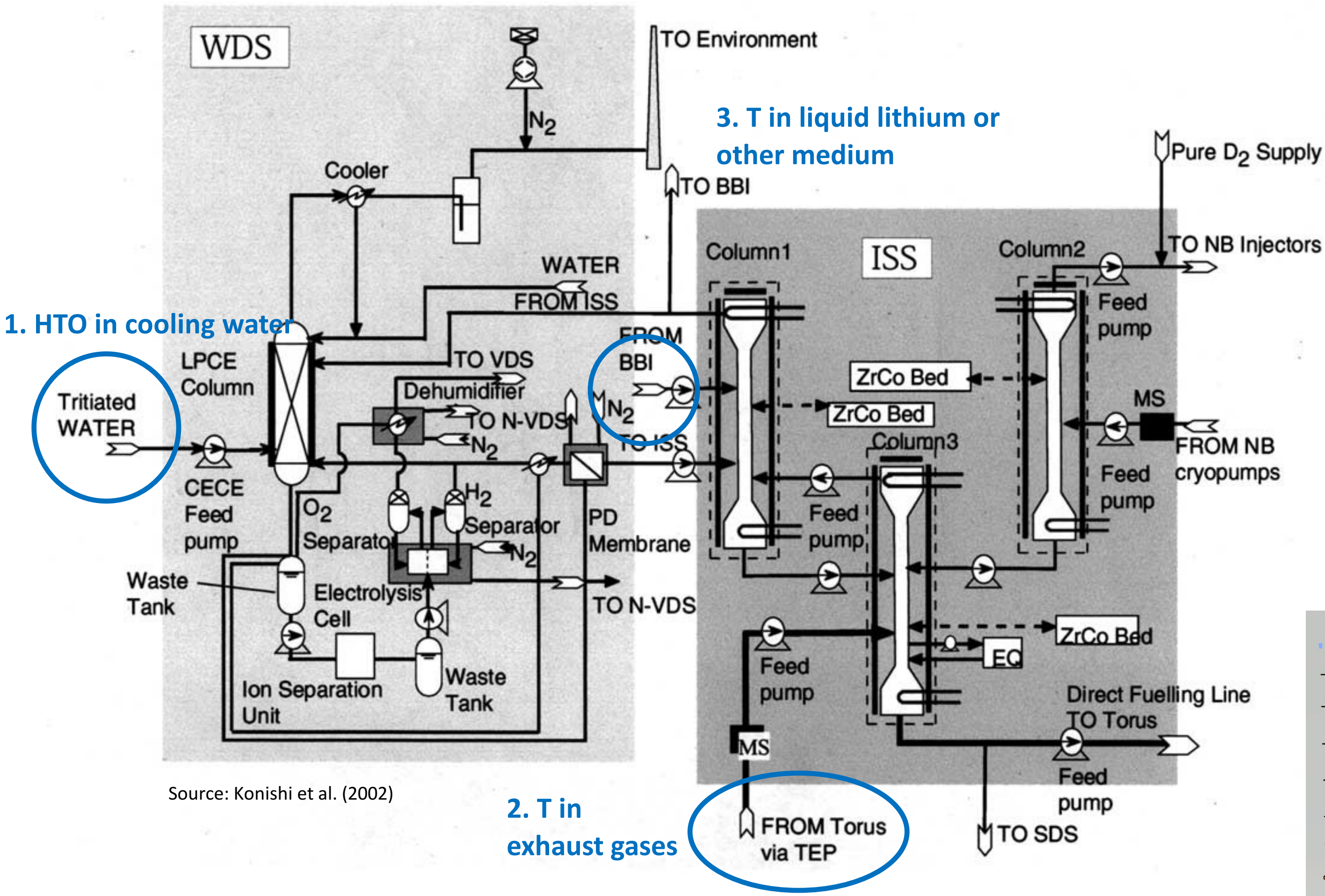
- Quantifying the uncertainty introduced by multiple shielding technologies and unknown performance could be a positive outcome of the cost study

Fuel cycle: there is not enough tritium (T) supply to burn without breeding + recycling

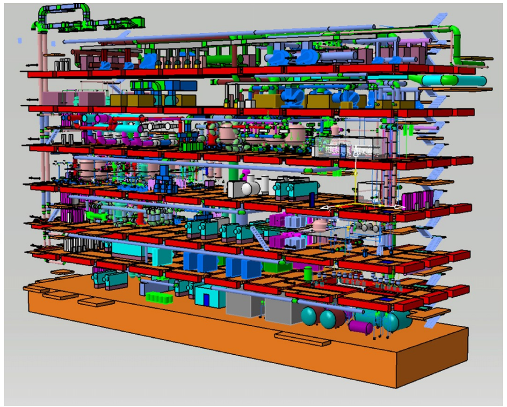


1 – Ni et al., "Tritium supply assessment for ITER and DEMOnstration power plant." *Fusion Engineering and Design*, 88 (2013)
2 – Sawan, M. and Abdou, M., "Physics and technology conditions for attaining tritium self-sufficiency for the DT fuel cycle." *Fusion Engineering and Design,* 81 (2006)

As currently conceived, Tritium Extraction Plants are large chemical processes



Source: Konishi et al. (2002)



Source: M. Gugla et al.

How will technology evolve? Commodity part of BOP, or as large, one-off, expensive subsystems? ALPHA project teams will benefit from mainline R&D.

Thank you

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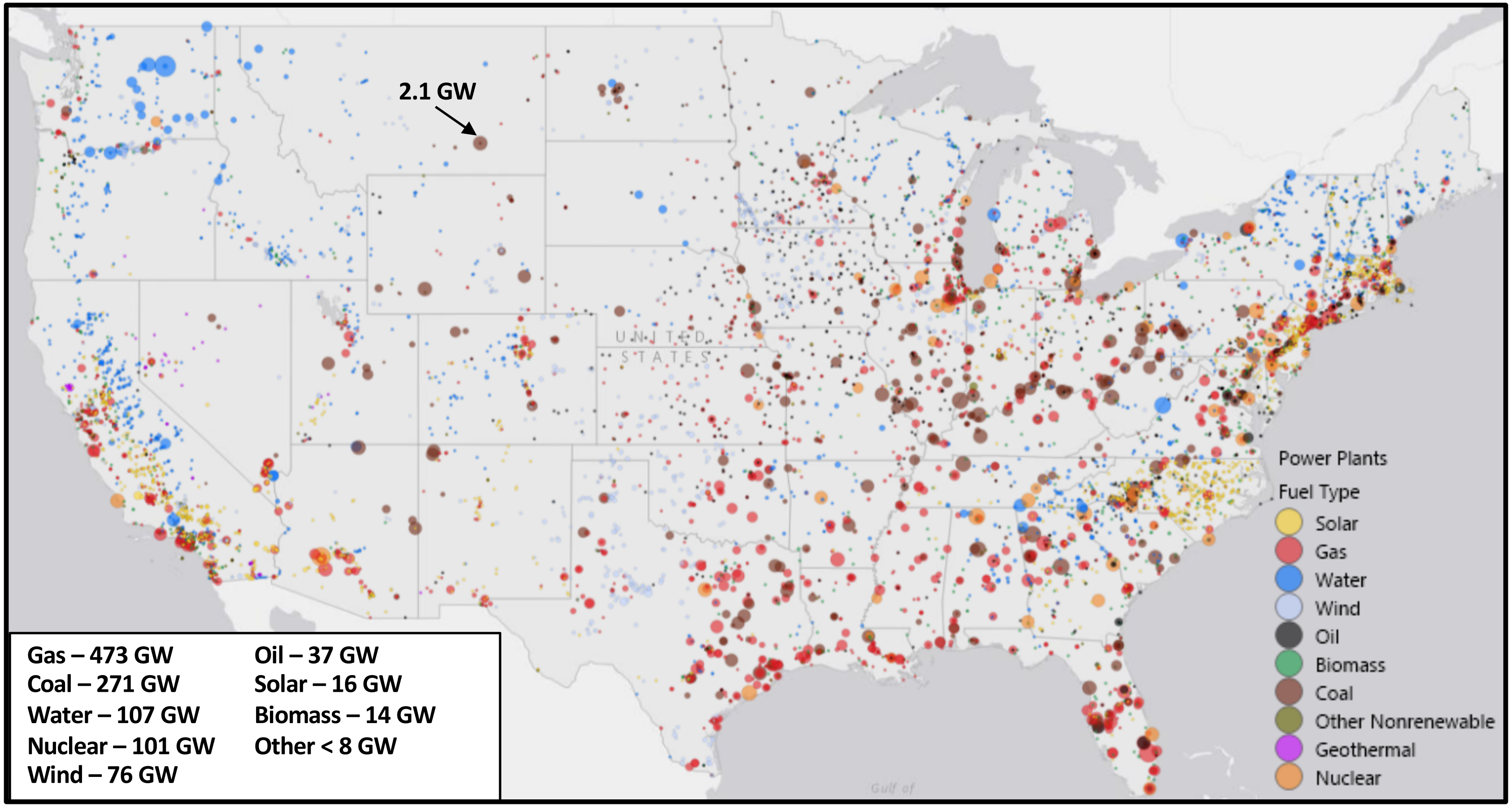
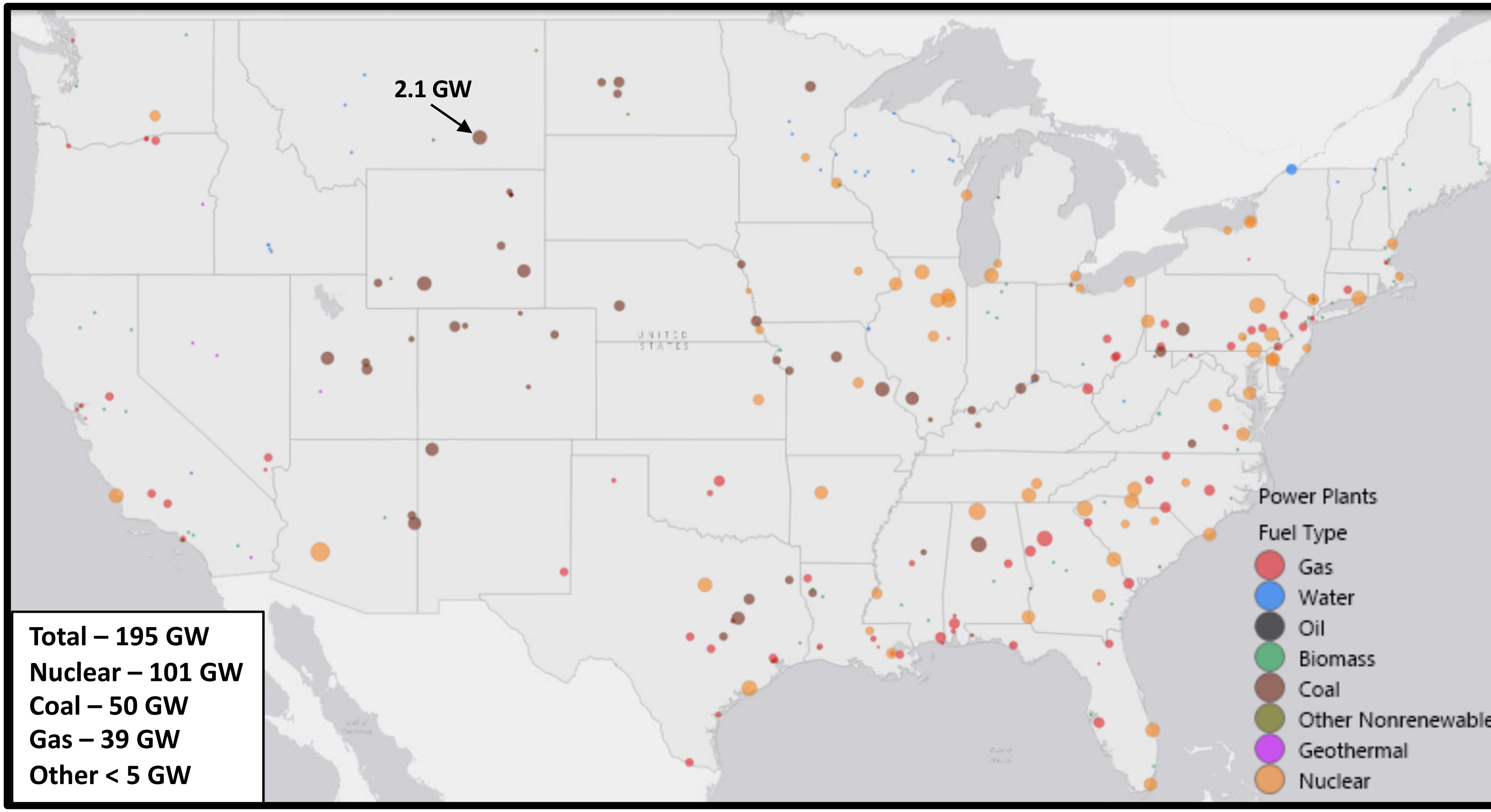
What does the domestic generating fleet look like, and what might Fusion displace / replace?

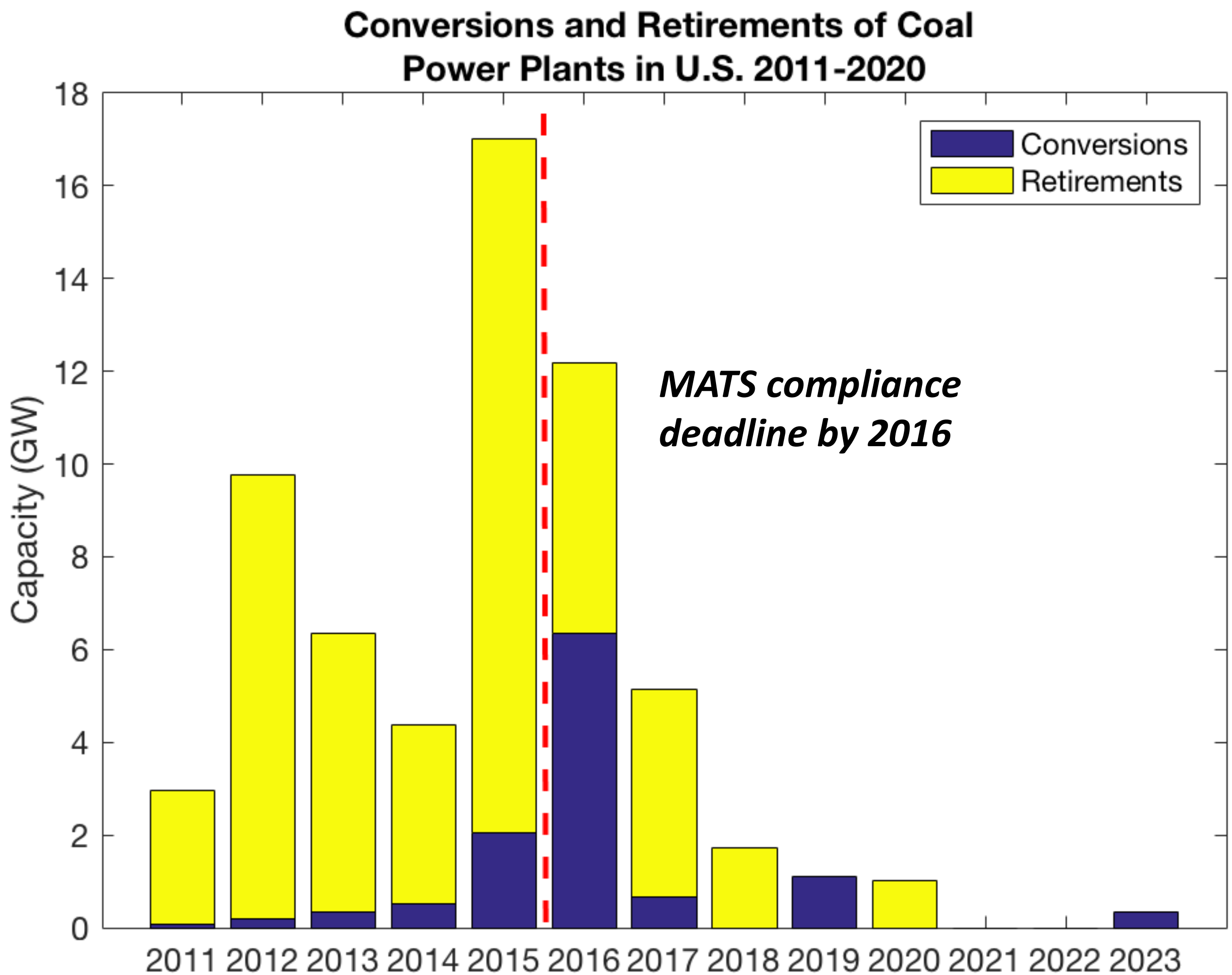


How much of the fleet currently operating as baseload year-round (CF > 70%) ?



Total – 195 GW
Nuclear – 101 GW
Coal – 50 GW
Gas – 39 GW
Other < 5 GW

In 2015-2016, conversions and retirements of coal-fired power plants were driven by EPA Policy



Announced as of 2/2016 (not projections)

Burn Rate (BR) and Tritium Breeding Ratio (TBR) are two important parameters for self-sufficiency

Larger Tritium Breeding Ratios will make-up for losses and produce excess fuel for ne reactors

A large Burn-up Fraction requires a smaller tritium inventory on hand

$$TBR = \frac{T_{bred}}{T_{burnt}}$$

$$BF = \frac{T_{burnt}}{T_{burnt} + T_{recycle}}$$

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Larger Tritium Breeding Ratios will make-up for losses and produce excess fuel for ne reactors

$$TBR = \frac{T_{bred}}{T_{burnt}}$$

$\downarrow$

Mostly agnostic to source of 14.1 MeV neutrons

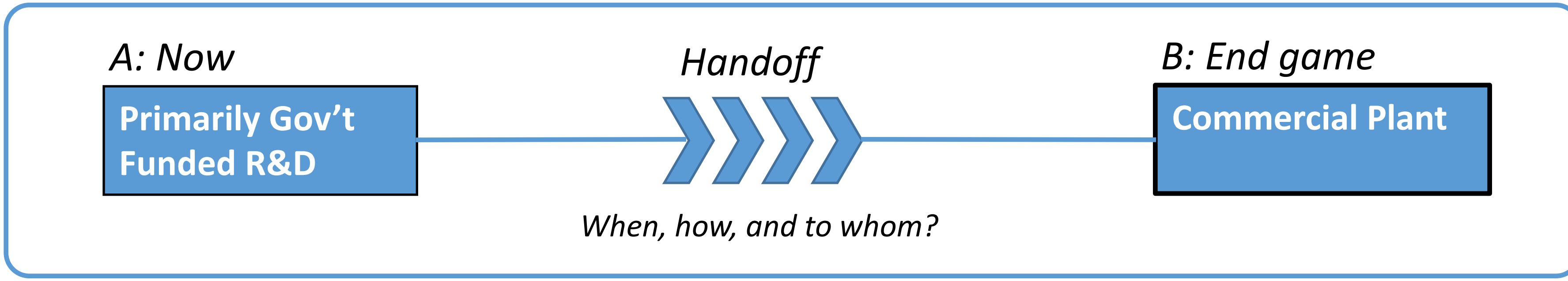
A large Burn-up Fraction requires a smaller tritium inventory on hand

$$BF = \frac{T_{burnt}}{T_{burnt} + T_{recycle}}$$

$\downarrow$

Fusion power core "performance" metric

Why does it matter, who will care?



Fusion development goal: First pre-commercial demonstration plant

The Tritium Extraction Facility (TEF) needed for a fusion power plant is larger than has ever been built

~3 kg - Annual Tritium Load at Darlington Tritium Removal Facility (Canada)

>56 kg - Annual Tritium Load at Tritium Extraction Plant for a 1 GW_{fus}

Inflows of Tritium at an Extraction Plant:

1. Coolant Loop → DTRF currently extracts tritium from heavy water
2. Tritium breeding material → Savannah River Site ($500M) extracts tritium from spent fuel rods. Limited experience extracting from liquid lithium.
3. Exhaust gas → Experience at tokamak experiments (JET in UK, TFTR at Princeton)

How will technology evolve? Is the right analogy air separation units at thermal power plants? Or as large, one-off, expensive subsystems?

Constraint: Mass flow rate / exhaust flow rate

- Constraint: exhaust and/or waste material cannot interfere with high-frequency pulses

- What is the magnitude of exhaust and/or waste material envisioned?

- What level of vacuum is needed (rough, middle, or high vacuum)?

For the Cost Study:

- Dependency between mass transport – geometry – cost

Bill on 2012-01-31 at 13:59 said:

The hubris of man: attempting to create a tiny artificial sun in order to boil an egg.